TIME DOMAIN ELECTROMAGNETIC SURVEYS FOR ASSISTING IN DETERMINING THE GROUNDWATER RESOURCES ON KAONOULU RANCH, LLP PROPERTY ISLAND OF MAUI

Project Number 5147

July 2009

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1.0 INTRODUCTION

This report contains the procedures and results of surface Time Domain Electromagnetic (TDEM) geophysical surveys performed for groundwater resource evaluation on portions of Kaonoulu Ranch, LLP (Kaonoulu Ranch) property in the Makawao District, Island of Maui. Zapata Incorporated, Blackhawk Division (ZAPATA/Blackhawk) conducted the surveys from June 16 through June 18, 2009 for Kaonoulu Ranch, LLP located in the town of Kula, Maui.

The main objective of the TDEM surveys was to explore for basal and high-level groundwater occurrences on the Kaonoulu Ranch property. The surveys were conducted at four TDEM sites to help determine the location for a future groundwater well on the property. Figure 1-1 shows the locations of TDEM soundings taken during this survey on the ranch property.

TDEM is a geophysical method that determines from the surface the geoelectric section (resistivity layering) of the subsurface. From the geoelectric section, information about geology and water quality can be inferred. This is possible because the electrical resistivity of the earth depends on lithology, porosity, the degree of saturation, and concentration of dissolved solids in the groundwater. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for water well placement and well completion depths.

2.0 GEOLOGY/HYDROGEOLOGY

Groundwater resources occur on the Hawaiian Islands basically in two modes:

- In a basal mode where a lens of fresh water floats on seawater, and
- In a high-level mode where the fresh groundwater occurrence is controlled by damming structures (i.e. intrusives, dikes, etc).

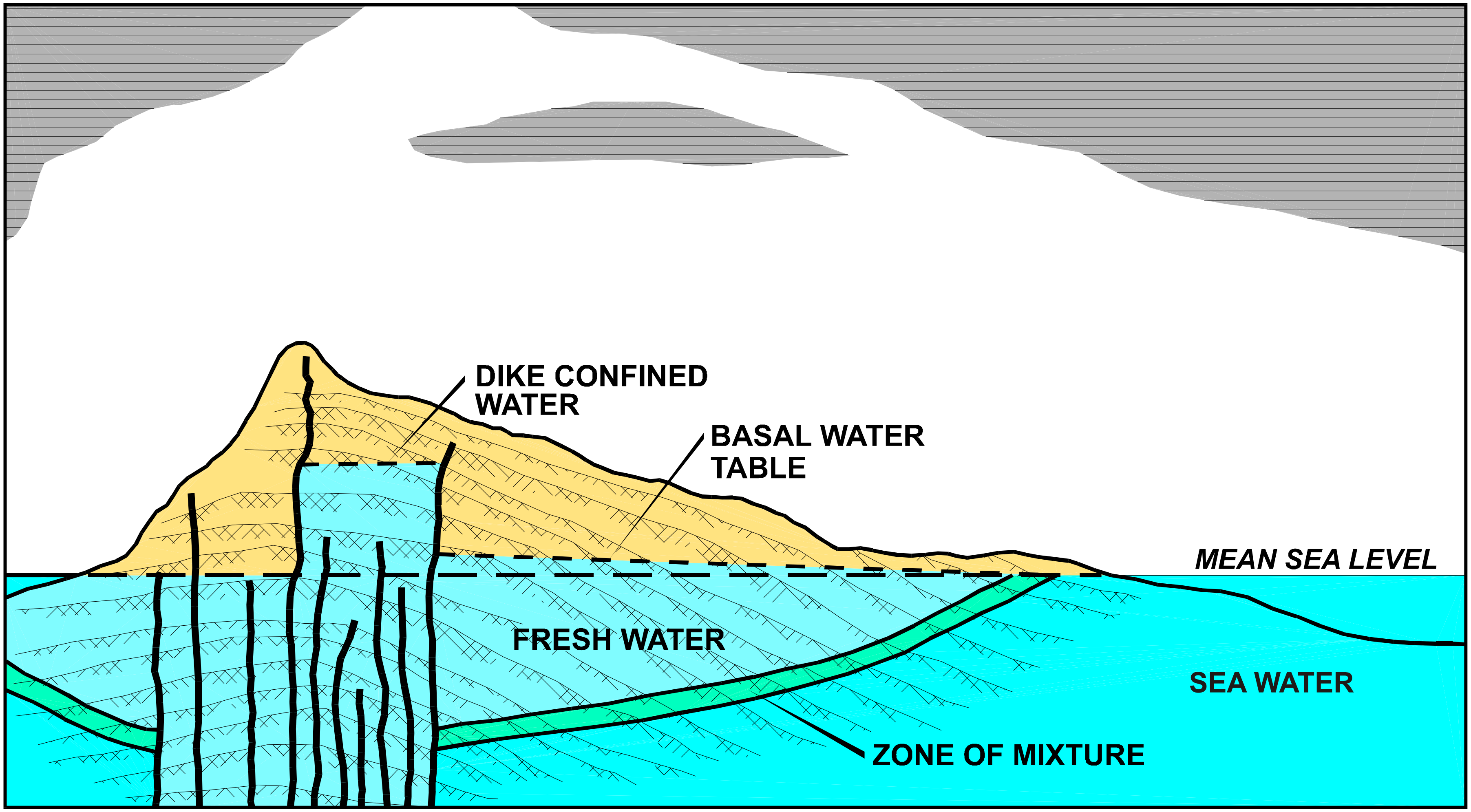
The basic geologic and hydrologic framework of the Island of Maui and the two modes of groundwater occurrences are illustrated in Figure 2-1. Fresh groundwater may also occur in areas between these two modes, but production is expected to be highly variable. TDEM surveys previously taken on Maui have reliably mapped basal mode groundwater and the boundary between fresh water in the basal mode and high-level water occurrences.

Basal mode groundwater is resting approximately at sea level near the ocean surrounding the Island of Maui. This is generally due to the fact that the volcanic rocks, which comprise the island, allow rainfall to percolate with little impedance directly downward through the rock mass (reference Figure 2-1). The fresh water floats directly on seawater encroaching from the ocean. Fresh water flows laterally toward the ocean causing the fresh water lens to be thinner near the shore line. When groundwater is under static equilibrium conditions, the Ghyben-Herzberg Principle states that for every one foot of fresh water above sea level approximately 40 feet of fresh water will exist below sea level (shown in Figure 2-2). The change from fresh water to seawater (transition zone) at depth may be relatively sharp (i.e. occurring over several tens of feet) or more gradual, depending upon hydrologic flux, horizontal and vertical permeability contrast, and other geologic factors. It is assumed, when resolving TDEM sounding data, that seawater saturated volcanics occur at the midpoint of the transition zone.

TDEM surveys are utilized to map the resistivity stratification of the subsurface. From numerous TDEM surveys on Maui and calibration at groundwater wells, characteristic ranges of subsurface resistivities have been derived for the geologic/hydrologic units shown in Figure 2-3. Some overlap in resistivity values occurs between the units; however, other factors (such as elevation) can be used to help separate the units. Therefore the main geologic/hydrologic units that can be derived from TDEM surveys are:

- Depth to seawater saturated volcanic rocks. This occurs in basal mode situations, and by using the Ghyben-Herzberg principle, the thickness of the basal fresh water lens can be calculated.
- Weathered volcanic layers (laterite). These lower resistivity units are generally relatively thin layers (100 ft to 200 ft thick) that generally occur at or near the ground surface.
- Clay poor and fresh water saturated volcanic rocks. These formations generally exhibit high resistivity values. The extent of fresh water saturation is normally based on geographic and elevation information, and it should be noted that fresh water cannot usually be directly detected in the TDEM data.

Groundwater damming structures (i.e. intrusives, dikes) are inferred with TDEM data by uncharacteristic sounding curves (distorted by 2-D structures), and by soundings that transition between detection of seawater at depth (indicating basal mode groundwater) and soundings that map high resistivities to depths below sea level (indicating high-level groundwater).



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Kula, Maui

Schematic Hydrogeologic Cross-Section
Island of Maui

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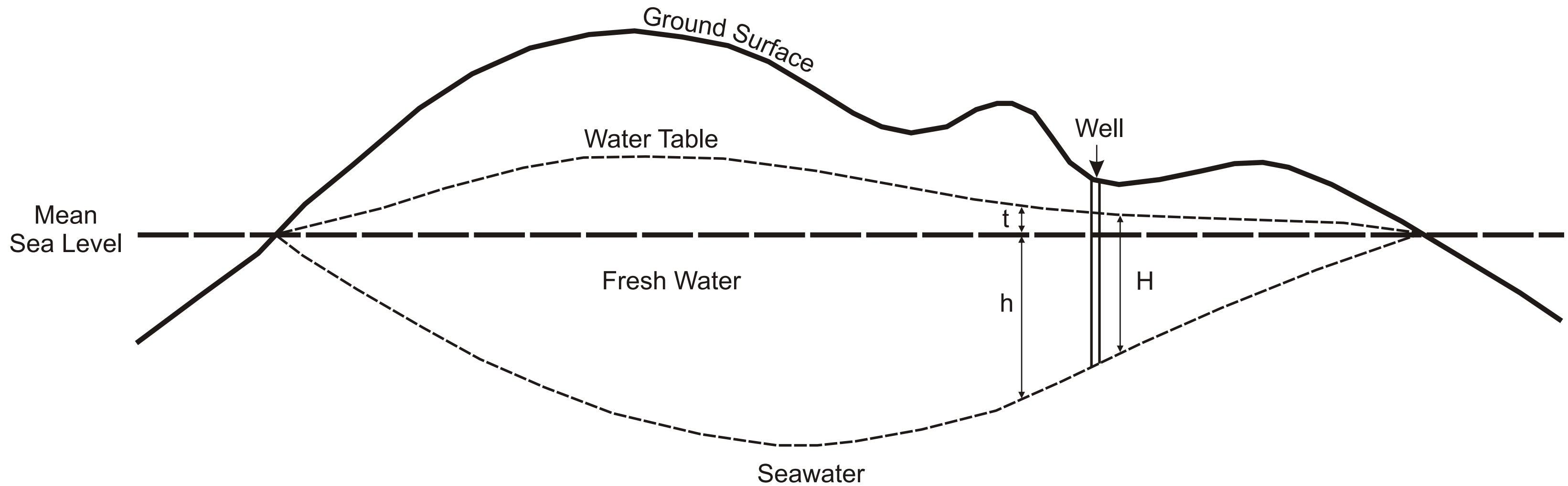

$$t = 1/40\ (h)$$

From: Ghyben-Herzberg

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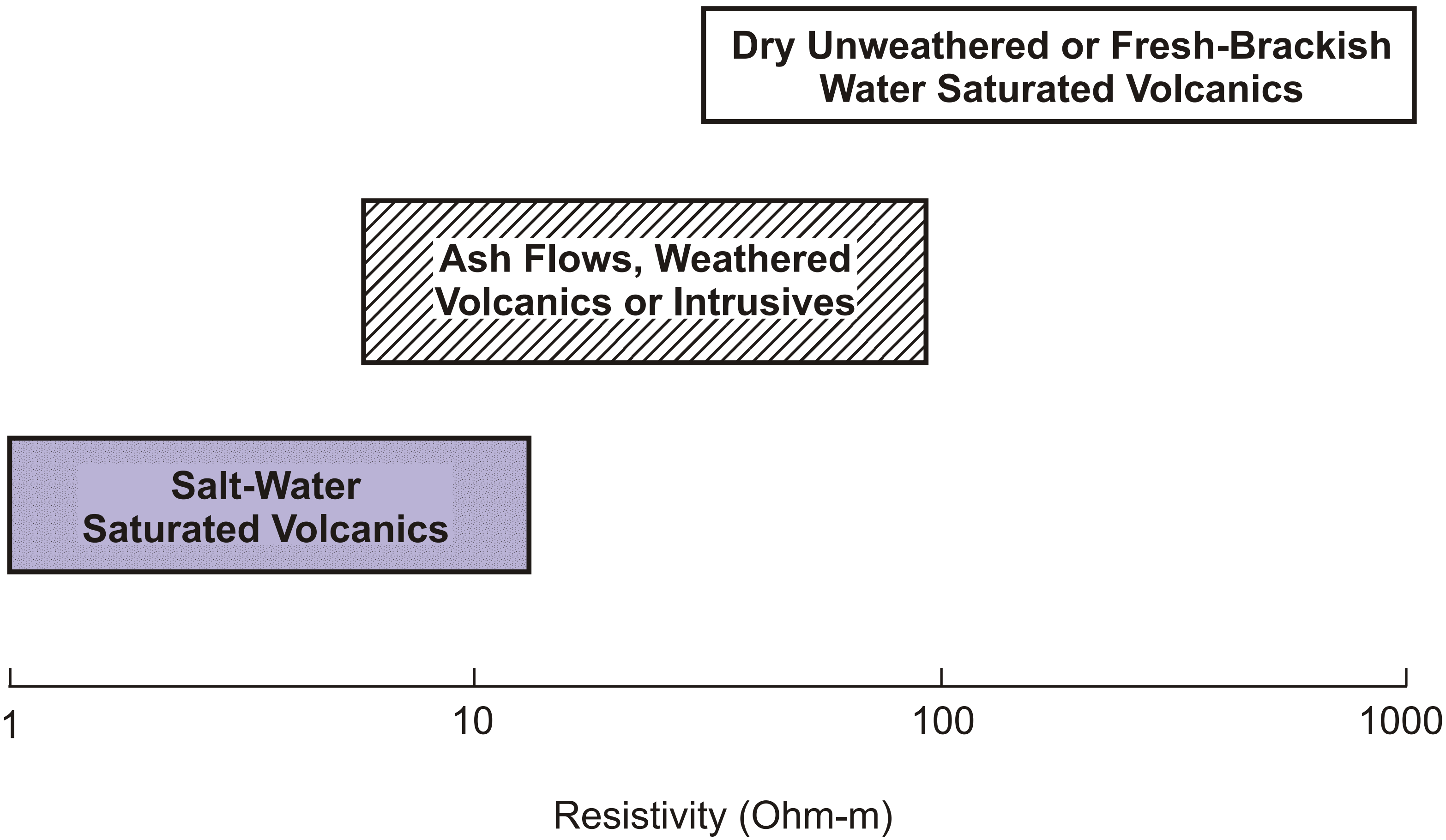

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Characteristic Resistivity Ranges
Island of Maui

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3.0 DATA ACQUISITION AND LOGISTICS

ZAPATA/Blackhawk mobilized a field crew consisting of a project geophysicist and geophysical technician to perform the geophysical surveys on the Kaonoulu Ranch property located along State Highway 37 near Kula, Maui. The ZAPATA/Blackhawk field crew and TDEM equipment were mobilized from Golden, Colorado to Kahului, Maui. Prior to conducting the surveys, ZAPATA/Blackhawk personnel coordinated with Doug Peterson (Kaonoulu Ranch Manager) and Tom Nance of Tom Nance Water Resource Engineering (TNWRE) to determine property access and locations for the TDEM soundings. During the course of the field work, Tom Nance also provided project direction and oversight. A daily log of field activities during the TDEM surveys is presented in Table 3-1.

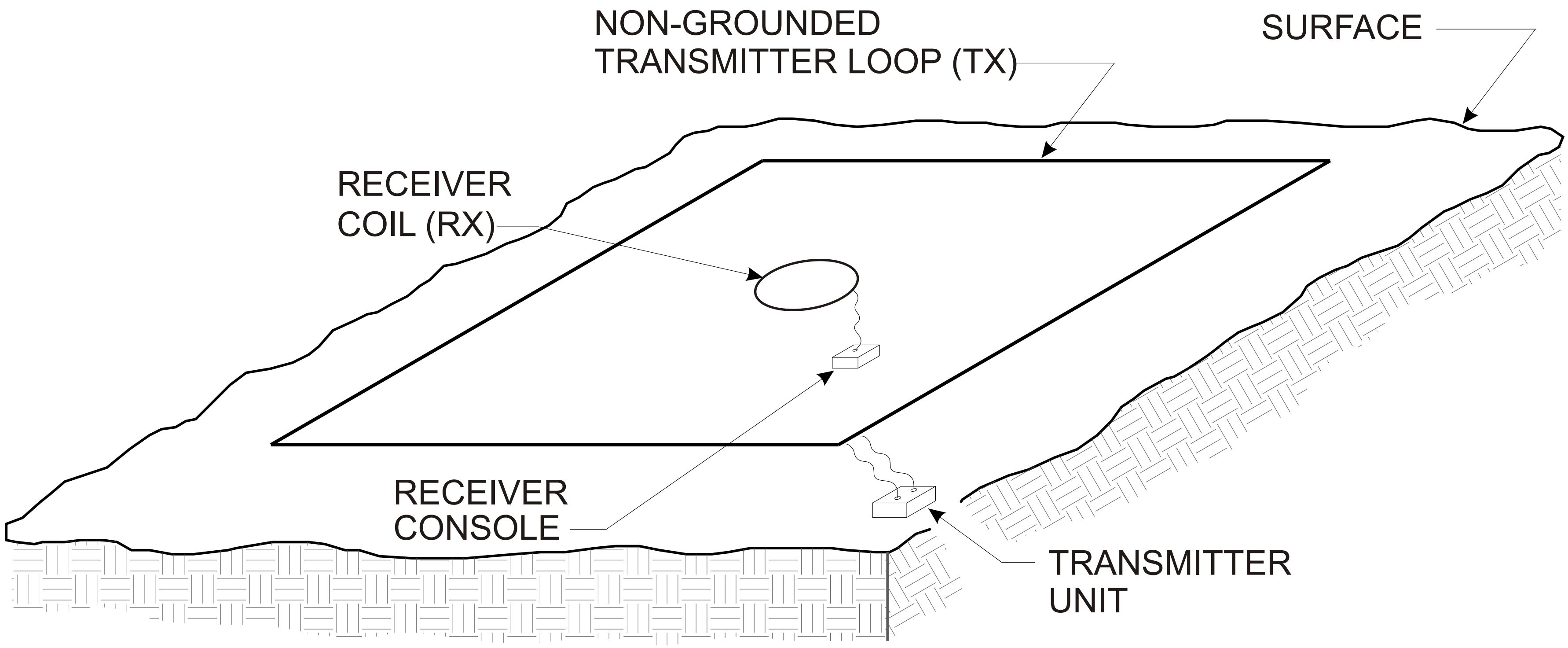
The Geonics EM37 geophysical system was utilized for the TDEM surveys. The EM37 system contains both a portable motor-generator powered transmitter and a PROTEM digital receiver. The main purpose of the TDEM measurements is to derive both the vertical and lateral variations in the geoelectric section (resistivity) of the subsurface. To accomplish this, TDEM soundings were collected using a central-loop array at each site. The square transmitter wire-loops were constructed using 12-gauge insulated copper wire laid on the ground surface, as illustrated in Figure 3-1. The dimensions of the transmitter wire-loops ranged from 1,000 ft by 1,000 ft to 1,500 ft by 1,500 ft. The motor-generator and transmitter were placed at a corner of each transmitter loop and square-wave current pulses were driven through the wire using a current ranging from 12 to 14 amperes. The current pulses induce eddy current flow in the subsurface of the ground. A receiver coil (1-meter diameter) attached to the PROTEM receiver was positioned in the center of each wire-loop and used to record the decay of the secondary magnetic field from the eddy currents induced in the subsurface. The effective exploration depth of a 1,000 ft-by 1,000-ft transmitter wire-loop array has been determined to be approximately 2,500 ft below ground surface. Therefore, at surface elevation of 1,000 ft, a search depth of about -1,500 ft below sea level (bsl) is obtained. Greater exploration depths are reached with larger wire-loops and several factors that affect the depth of investigation include ground resistivity (ohm-m) and surrounding ambient cultural interference (i.e. 60-cycle powerline, pipelines, etc). A technical note describing the principles of TDEM with case histories is given in Appendix A.

The TDEM data acquired at each sounding location consisted of measurements utilizing several receiver gain settings (5, 6, and 7) and two transmitter frequencies in order to ensure data quality and to obtain data over the longest possible time interval. The data were recorded at base frequencies of 3 Hz and 30 Hz to ensure maximum search depth for each TDEM sounding. For data quality control (QC) purposes, additional data were collected at four designated locations (200 ft offset in each direction from the center), for comparison to the central-loop data. The data from each sounding were stored in solid-state memory in the PROTEM receiver and transferred daily to a PC for processing. The TDEM data collected with the PROTEM receiver were of excellent quality. However, Sounding KAO-2 data was determined to be affected (distorted) by local cultural interferences (i.e. metal fence line), likely from a combination of a nearby power line and metal post fence line located running along the west and east side of this transmitter wire-loop.

The corners of each transmitter wire-loop were registered to local dirt roads on the ranch property. Other landmarks, such as power line, corrals (fences) and gates were also used to position the corners of the wire-loops on the topographic map with a hip-chain and compass. In addition, a hand-held global positioning system (GPS) was utilized to locate the center and transmitter location (corner) of each sounding. The GPS coordinates were used to position each loop center on the geo-referenced topographic map and the elevation was subsequently derived from that position. A total of four TDEM soundings were measured on the ranch property during the three days of fieldwork. GPS coordinates and elevations of the TDEM soundings, gates, and the intersection of power line and dirt road are given in Table 3-2 in Appendix B.

Table 3-1
Daily Log of Field Activities
Kaonoulu Ranch, LLP TDEM Survey

Date (2009)	Activity
June 9	Ship TDEM geophysical equipment from Golden, CO to Kahului, Maui.
June 15	Mobilize Blackhawk field personnel from Golden, CO to Kahului, Maui. Unpack equipment at hotel and organize into 4WD vehicle.
June 16	Test motor-generator, EM37 transmitter and PROTEM receiver. Drive to Kaonoulu Ranch gate (on Hwy 37) and meet with Ranch Manager. Perform recon of Loop 1. Begin TDEM survey. Lay out wire-loop and collect data on Sounding KAO-1. Download data to PC and perform preliminary data analysis. Discuss results with TNWRE.
June 17	Lay out wire-loop and collect data on Sounding KAO-2. Pick up wire-loop, move to Sounding KAO-3 and acquire data. Download data to PC and perform preliminary data analysis. Discuss results with TNWRE.
June 18	Lay out wire-loop and cut abandoned 2" metal pipe line into 100 ft sections; collect data on Sounding KAO-4. Download data to PC and perform preliminary data analysis in field. Discuss results with TNWRE. Decision is made by TNWRE and Ranch Manager that the TDEM survey is finished. Pick up wire-loop and complete project.
June 19	Pack up TDEM equipment into shipping boxes and deliver to FedEx office in Kahului.
June 20-21	Days off.
June 22	Demobilize Blackhawk personnel from Kahului, Maui to Golden, CO.



BLACKHAWK A DIVISION OF ZAPATAENGINEERING	**Kaonoulu Ranch, LLP** *Kula, Maui*	**Schematic layout of TDEM system with locations of TX and RX for Central Loop Array measurements**

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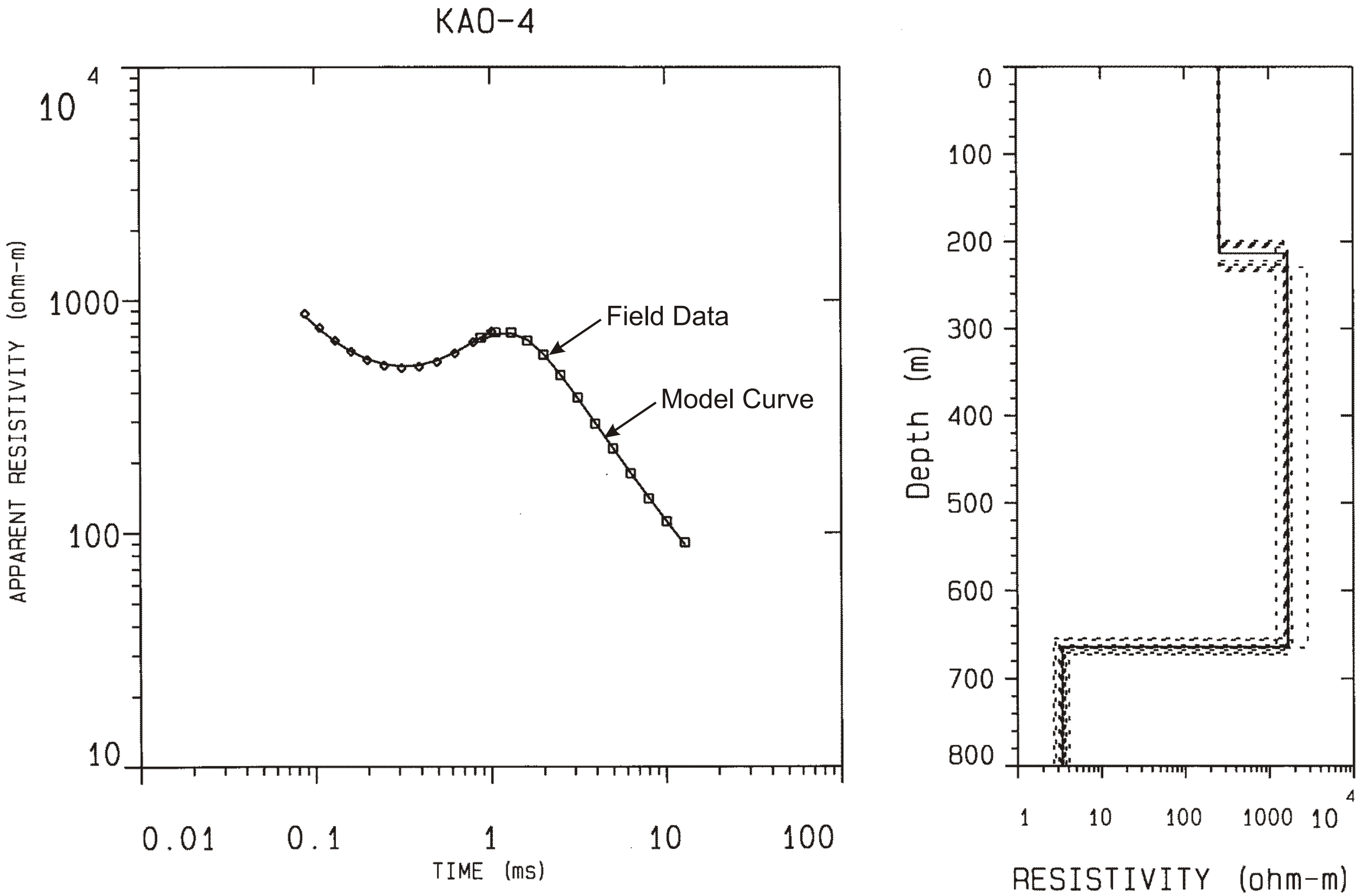
4.0 DATA PROCESSING

The geophysical field data collected for each TDEM sounding was transferred from the Geonics PROTEM digital receiver to a PC for editing and processing. Processing of the TDEM data starts with averaging of the electromotive forces recorded for positive and negative receiver polarities. Next, the measurements collected at two base frequencies (3 and 30 Hz) and amplifier gains are combined to give one voltage decay curve (transient). The electromotive forces collected from 20 logarithmical spaced time-channels (gates) of the decay curve are subsequently entered into the TEMIXXL (Interpex Ltd) inversion program. The data are used to obtain a one-dimensional (1-D) geoelectric section that best matches the observed (field data) decay curve.

The TEMIXXL inversion program requires an initial model of the geoelectric section measured. The initial model includes the number of layers, resistivities and thickness for each of the layers. This model is usually derived from knowledge of the geologic section or from data obtained from drill holes or electric logs. The inversion program is then allowed to adjust the layer thickness and the resistivities, so that the model curve converges to best fit the field data. The inversion program does not change the total number of layers within the model curve, but allows all other parameters to change freely or they can optionally be fixed constant. To determine the influence of the number of layers on the solution, separate inversions with a different number of layers are run. Subsequently, the model with the least number of layers that best fits the field data is used.

An example of the output of the inversion program is shown on Figure 4-1 for Sounding KAO-4. This figure shows the measured data points (in terms of apparent resistivity) superimposed on a solid line on the left panel. The solid line represents the computed forward model for the geoelectric section on the right panel. This geoelectric section is the best match obtained by the inversion program. Figure 4-2 shows the tabulated inversion parameters consisting of measured data, computed data for best match solutions and an example of the table of inversion statistics. A three-layer inversion model is shown for Sounding KAO-4. The model displays a relatively thick (700 ft) resistive (259 ohm-m) upper layer overlying a resistive (1653 ohm-m) second layer. The third layer exhibits a very low resistivity (3.4 ohm-m) and the depth to the top of the third layer is modeled at -198 ft below sea level (bsl) in the section. The third layer is interpreted as conductive seawater.

The interpreted geoelectric section derived from each TDEM sounding is not unique. The magnitude of each individual layer resistivity and thickness can normally be varied within a limited range with no significant change to the fit of the geoelectric model of the data. This variation is termed equivalence. An equivalence analysis was performed for each TDEM sounding. Both Figures 4-1 and 4-2 also show the equivalence analysis for Sounding KAO-4. This sounding is typical of the TDEM data which shows a +/-5% equivalence in depth determinations and +/-10% in individual layer resistivities. The inversion results for each sounding at the Kaonoulu Ranch are given in Appendix B.



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Sounding KAO-4
Example Inversion Output
Apparent Resistivity Curve
Island of Maui

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DATA SET: KAO-4

CLIENT: Kaonoulu Ranch LLC DATE: 06-18-09
LOCATION: Maui, Hawaii SOUNDING: 4
COUNTY: Maui ELEVATION: 603.50 m
PROJECT: Kaonoulu Ranch EQUIPMENT: Geonics PROTEM
LOOP SIZE: 457.000 m by 457.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 4.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 1.887 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			603.5	1980.0	
1	258.8	213.6	389.8	1278.8	0.825
2	1653.8	450.3	-60.49	-198.5	0.272
3	3.38				

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	252.230	258.866	266.959
	2	1206.475	1653.867	2837.147
	3	2.679	3.381	4.096
THICK	1	199.308	213.643	234.271
	2	421.836	450.354	468.503
DEPTH	1	199.308	213.643	234.271
	2	654.329	663.998	672.788

Equivalence Analysis

CURRENT: 13.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 200.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.881	103.6	107.9	-4.17
2	1.06	58.98	61.03	-3.46
3	1.31	35.34	35.81	-1.33
4	1.61	23.58	23.34	1.02
5	2.00	17.05	16.93	0.708
6	2.50	13.25	13.16	0.671
7	3.14	10.49	10.59	-0.968
8	3.95	8.70	8.61	1.02
9	4.99	7.01	6.98	0.475
10	6.31	5.65	5.62	0.615
11	7.99	4.55	4.48	1.51
12	10.14	3.51	3.52	-0.204
13	12.87	2.64	2.73	-3.25

CURRENT: 13.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 200.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	0.0881	22984.5	23718.2	-3.19
15	0.106	17440.3	17837.4	-2.27
16	0.131	12638.6	12769.3	-1.03
17	0.161	8801.9	8777.2	0.280
18	0.200	5837.5	5758.8	1.34
19	0.250	3639.1	3563.7	2.07
20	0.314	2139.4	2085.9	2.50
21	0.395	1182.7	1154.0	2.43
22	0.499	613.6	601.3	2.00
23	0.631	300.5	297.3	1.04
24	0.799	141.1	141.1	0.0272
25	1.01	66.72	66.50	0.327

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.98				
P 2	-0.01	0.03			
P 3	0.02	-0.04	0.41		
T 1	-0.03	-0.13	0.10	0.91	
T 2	0.02	0.06	-0.10	0.05	0.96

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Sounding KAO-4
Example of Tabulated Data From Inversion

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5.0 INTERPRETATION AND RESULTS

5.1 TDEM SOUNDING DATA

From each TDEM sounding, the geoelectric section of the subsurface is derived. The results of the one-dimensional (1-D) inversion of the individual TDEM soundings can be linked together (layers with similar resistivities) to create a 2-D geoelectric cross-section along a survey line. A total of four (4) TDEM soundings were collected along a dirt road on the Kaonoulu Ranch property (reference Figure 1-1). From the TDEM surveys a single geoelectric cross-section was generated. The correlation between geoelectric layers and lithologic units, presented on Figure 2-3, was used to interpret the geoelectric cross-section.

5.2 GEOELECTRIC CROSS-SECTION – LINE 1 (A-A')

Figure 5-1 shows the layered geoelectric cross-section interpreted from TDEM data collected along Line 1. The TDEM soundings were located along a dirt ranch road on the north side of Na'alae Gulch in a roughly west to east direction. The center of Sounding KAO-1 was located at the 1,640 ft elevation level, below the power line. Sounding KAO-2 was positioned above the power line at the 1,800 ft elevation, and it was determined to be distorted by cultural interferences (i.e. fence line, power line, etc) which were located on both sides of the transmitter wire-loop. The position of Sounding KAO-2 is shown on the cross-section and labeled as distorted data and the geoelectric section was not used in the interpretation. The center of Sounding KAO-3 was located west of Sounding KAO-1 at the 1,470 ft elevation. Sounding KAO-4 was positioned east of the fence line at the 1,980 ft elevation level.

A three-layer cross-section is interpreted for each sounding along the survey line. The upper two layers in the geoelectric cross-section, beneath all the soundings, exhibit intermediate to high resistivities that range from 120 ohm-m to >1,000 ohm-m and are interpreted as dry, clay poor volcanic formations located both above and below sea level. Where the second layer occurs below sea level (>1,000 ohm-m), it is expected to be saturated with fresh-brackish basal mode water. The third layer in the section shows low resistivities (1.2 ohm-m to 3.4 ohm-m) and is interpreted to represent seawater saturated volcanic layers at depth beneath each sounding. The calculated thickness of the fresh-brackish basal water lens ranges from 71 ft (head of 1.8 ft) beneath Sounding KAO-3 to 198 ft (head of 4.9 ft) beneath Sounding KAO-4. The interpreted thinning of the basal water lens to 8 ft (head of 0.2 ft) shown beneath Sounding KAO-1 could be related to local subsurface geologic features (i.e. volcanic fissure vent, cinder cones). A subsurface geologic feature may be causing non-layered earth conditions (i.e. 2-D high angle fault, etc) that may act as a possible groundwater damming structure beneath this area of the property. There are, however, no surface geologic features mapped in the immediate vicinity of this sounding.

Information regarding a recently drilled water well in the area, located approximately 5,500 ft directly north of Sounding KAO-4 and above the power line at the 1,790 ft elevation, is reported to contain basal mode water with static water level (head) of 6.1 ft (per com Tom Nance), which is consistent with Sounding KAO-4.

5.3 HYDROGEOLOGIC INTERPRETATIONS

Table 5-1 contains the approximate thickness of the fresh-brackish water lens calculated from the elevation of the seawater interface interpreted from the TDEM soundings taken at the Kaonoulu Ranch property. The table includes the value of static water level (head) calculated by using the Gheyben-Herzberg Principle.

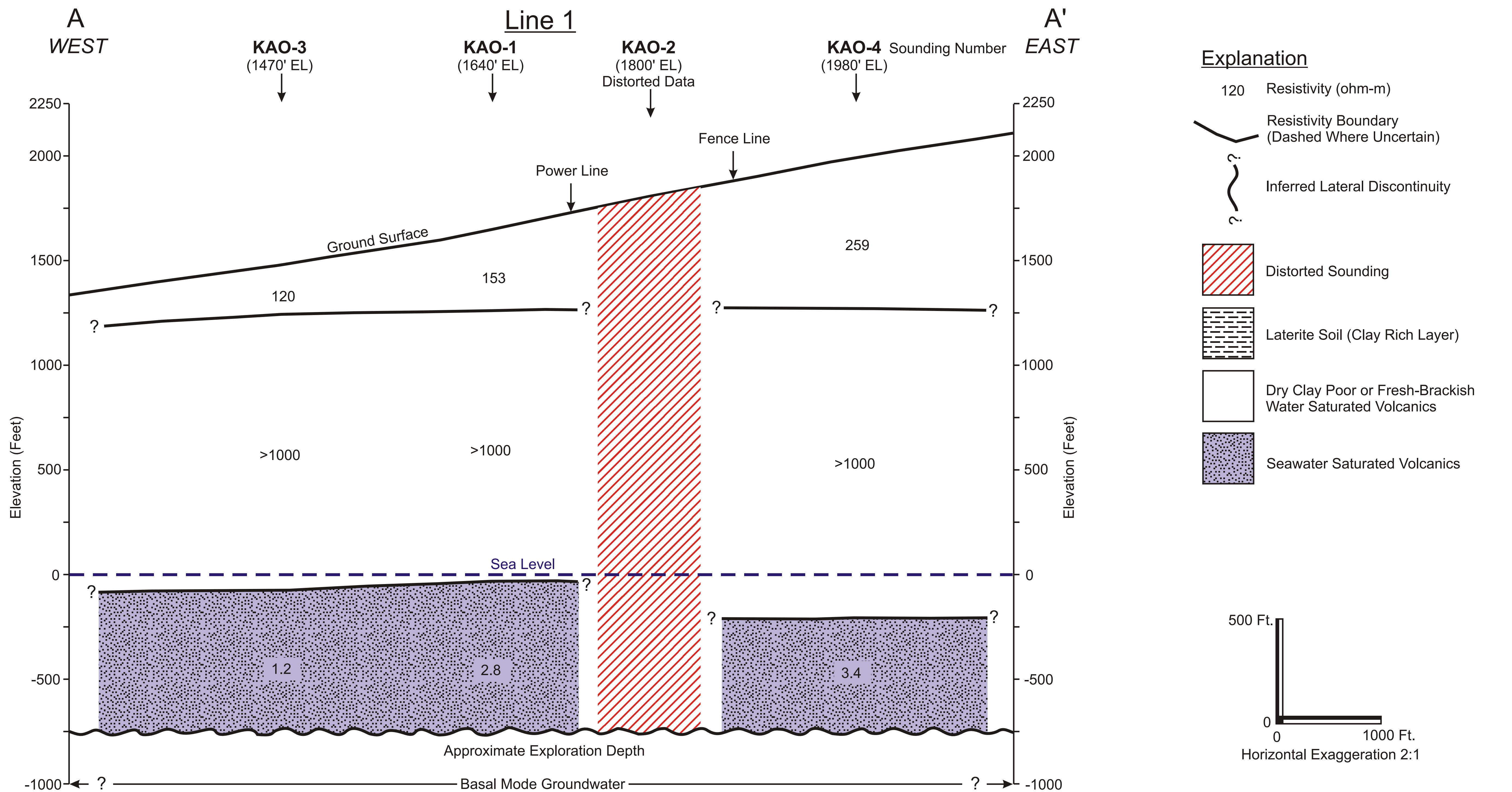
Table 5-1
Hydrogeologic Information Derived From TDEM Soundings
Kaonoulu Ranch Property
(Values in Feet)

Sounding Number	Surface Elevation	Elevation of Top of the Conductive Layer	Calculated Static Water Level (Head) Using Ghyben-Herzberg Principle	Approximate Thickness of Fresh-Brackish Water Lens
KAO-1	1640	-8	0.2	8
KAO-2	1800	*	*	*
KAO-3	1470	-71	1.8	73
KAO-4	1980	-198	4.9	203

*This TDEM sounding was determined to be distorted by cultural interferences (i.e. metal fence line, etc); therefore, a calculation cannot be made for the thickness of the fresh-brackish water lens.

The TDEM data is further summarized on the interpretation map shown in Figure 5-2. On this map all the soundings (blue) exhibit a low resistivity (1.2 ohm-m to 3.4 ohm-m) layer that was detected below sea level. A fresh-brackish water lens is interpreted to occur in the basal mode beneath these soundings. The thickest fresh-brackish water lens is expected to occur beneath Sounding KAO-4, with a potential thickness of 198 ft (head of 4.9 ft).

The accuracy of determining the depth to the salt water interface from TDEM soundings is estimated to be +/-5% of the total depth calculated in the sounding measurement, (e.g. from the ground surface to the salt water interface).



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Kula, Maui

Geoelectric Cross-Section from 1-D TDEM Inversions Line 1 A-A'
Makawao District, Island of Maui, Hawaii

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6.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM surveys on the Kaonoulu Ranch, LLP property was to explore for potential basal and high-level groundwater resources on the Island of Maui. The optimum locations for groundwater in the basal mode are expected to occur where the thickest lens of fresh-brackish water is detected floating on seawater. The optimum locations for high-level groundwater are expected to occur within dike-confined areas detected at relatively low surface elevations.

The results from the TDEM surveys are shown on Figures 5-1 and Figure 5-2 and Table 5-1. The general conclusions from the results indicate:

- That beneath Soundings KAO-1, KAO-3 and KAO-4, a lens of basal mode fresh-brackish water occurs. The thickest lens of potential fresh-brackish water resource is interpreted to occur beneath Sounding KAO-4, and it is estimated to be 198 ft thick (4.9 ft of head).
- That none of the soundings detected the presence of high-level groundwater.

Due to the location of the existing power line and metal fence line on the property, the size of the transmitter wire-loop for Sounding KAO-2 was increased in the north-south direction (to 1,500 ft), in an effort to maximum the transmitter loop moment. However, after analysis of the TDEM data, this sounding was determined to be distorted by surrounding cultural interferences (i.e. metal fence line, power line) and therefore was not used in the interpretation.

Because of the limited TDEM data at the Kaonoulu Ranch, the location for a potential high-level groundwater well was not determined. Therefore, additional TDEM soundings placed above (mauka) Sounding KAO-4 are recommended to help define the potential for high-level groundwater in this area of the property.

7.0 CERTIFICATION AND DISCLAIMER

All geophysical data analysis, interpretations, conclusions, and recommendations in this document have been prepared under the supervision of and reviewed by Zapata Incorporated, Blackhawk Division Senior Geophysicists.

This geophysical investigation was conducted using sound scientific principles and state-of-the-art technology. A high degree of professionalism was maintained during all aspects of the project from the field investigation and data acquisition, through data processing, interpretation, and reporting. All original field data files, field notes and observations, and other pertinent information are maintained in the project files and are available for the client to review.

A geophysicist's certification of interpreted geophysical conditions comprises a declaration of his/her professional judgment. It does not constitute a warranty or guarantee, expressed or implied, nor does it relieve any other party of its responsibility to abide by contract documents, applicable codes, standards, regulations, or ordinances.

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Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

(1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,

(2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

(3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

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electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) Land survey and space requirements.—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z-component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause negligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf$_z$, requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf$_x$ has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

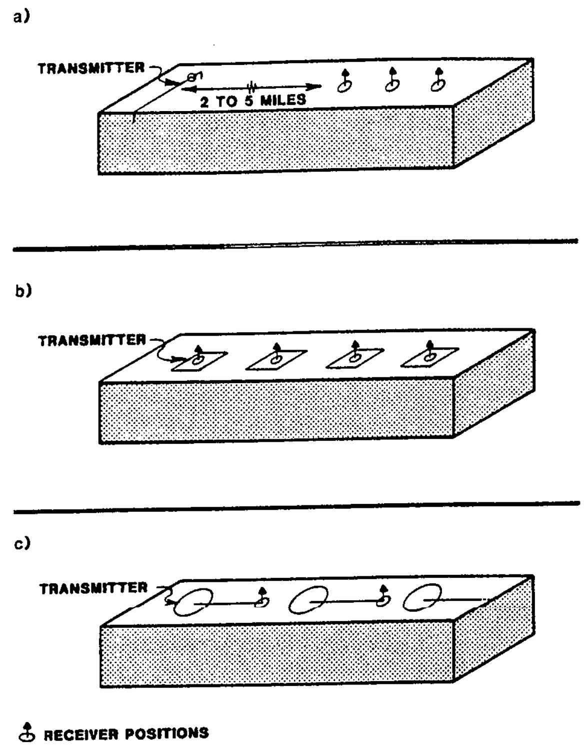


FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

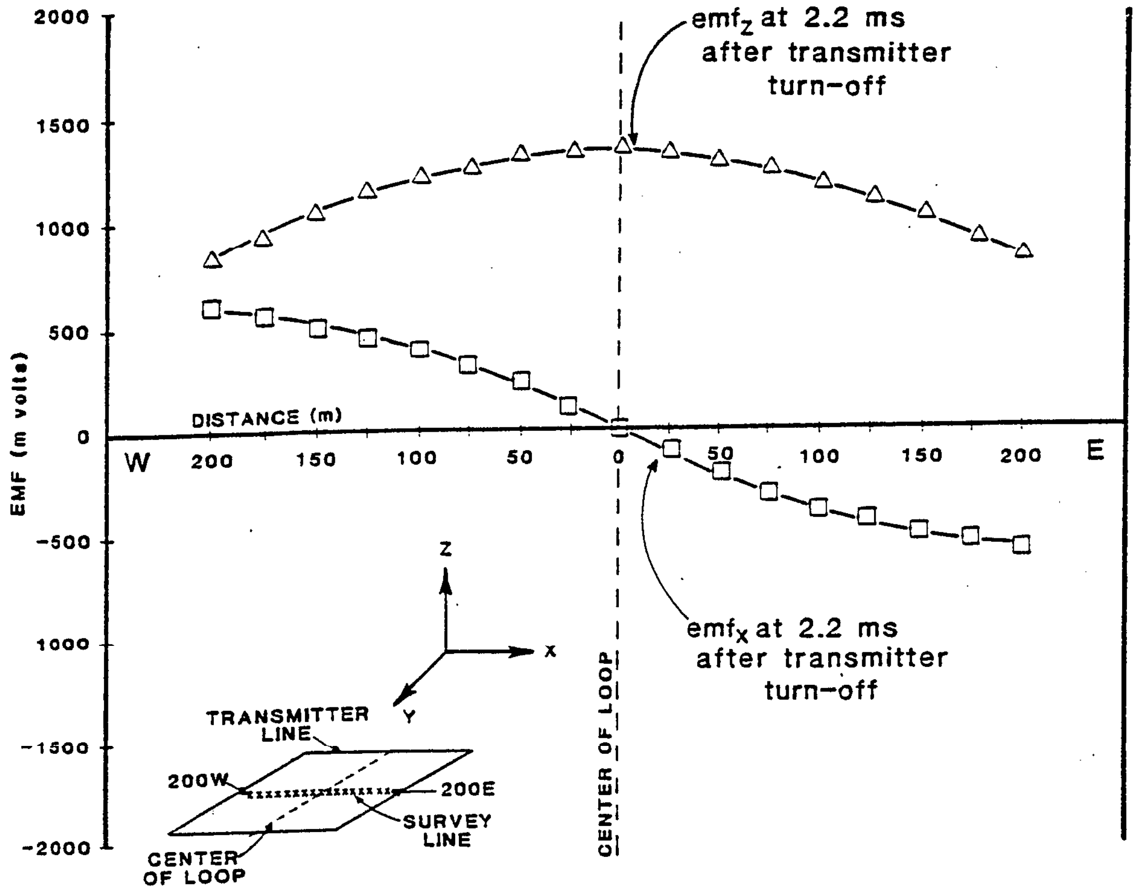


FIG. 2. Measured behavior of the electromotive forces due to vertical (emf$_z$) and horizontal (emf$_x$) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) Well-defined sounding plotting points.—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf$_z$ measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway between the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) Vertical resolution.—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf$_z$ at late time, is given by

$$\mathrm{emf}_z = \frac{\mu^{5/2}}{4\pi^{3/2}} \frac{\sigma^{3/2} M_t M_R}{t^{5/2}}; \qquad (1)$$

where

t = time after current turn-off,
σ = conductivity of uniform half-space,
μ = magnetic susceptibility,
M_t = moment of transmitter,
M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \tag{2}$$

where

$$\tau \text{ is } \sqrt{\frac{8\ \pi^2 t}{\mu_0\ \sigma}}.$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R. Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf$_z$ is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf$_z$) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transfered to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m^2 (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μs intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

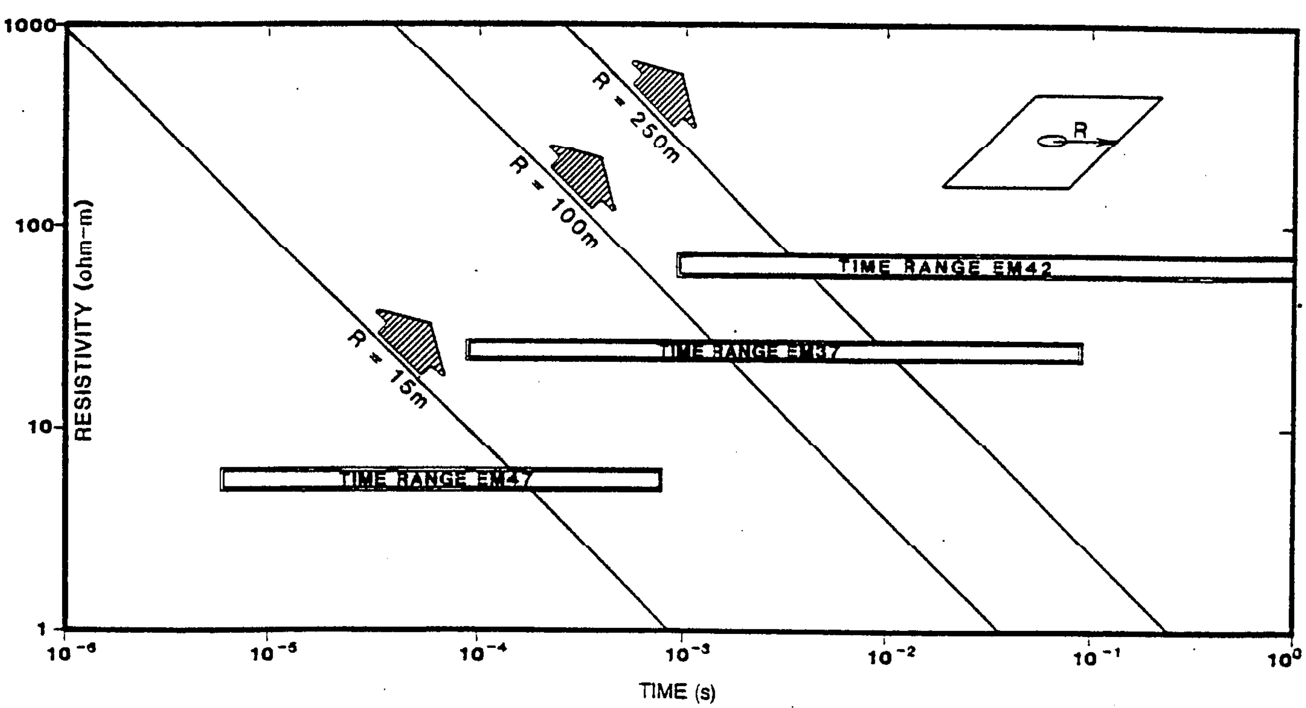


FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

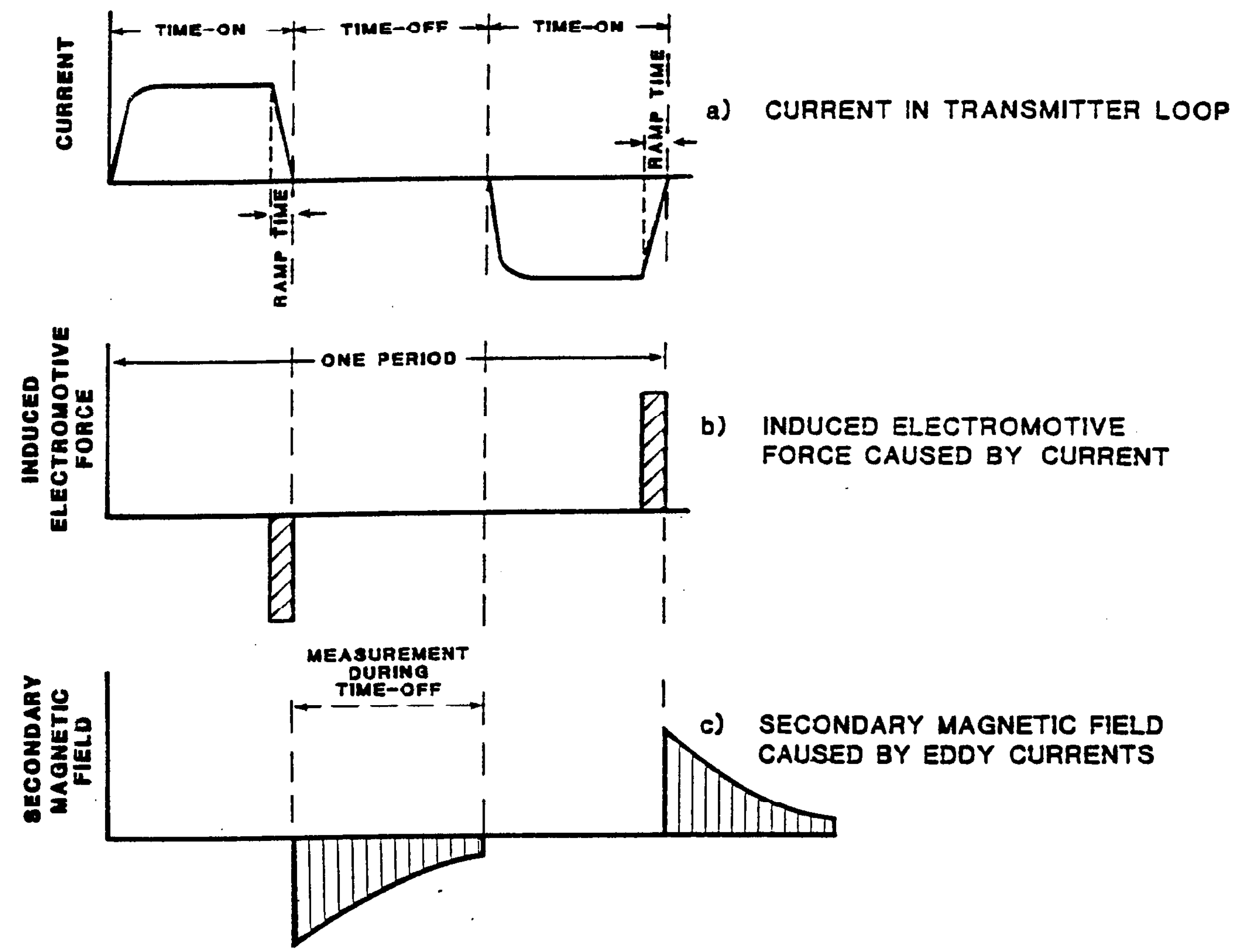
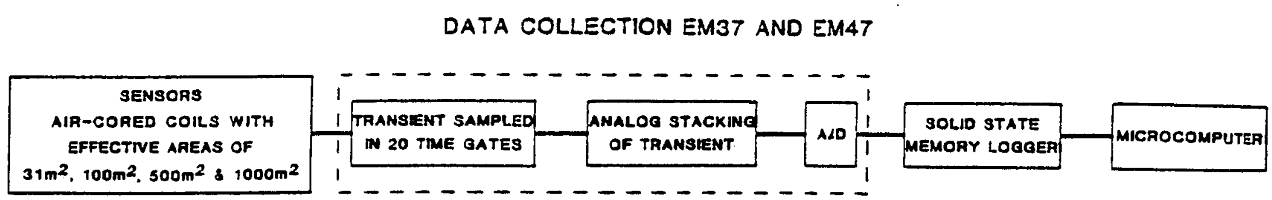
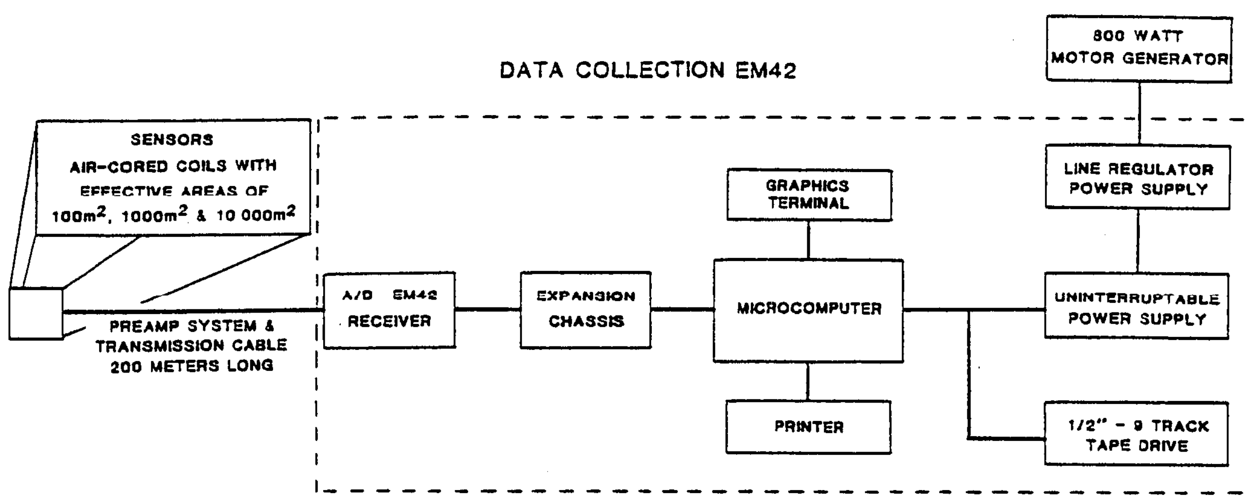


FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.



(a)



(b)

FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m^2

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf$_z$ decays as $t^{-5/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m^2 air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m^2 air coil and a base frequency of 0.075 Hz. When the 10 000 m^2 coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

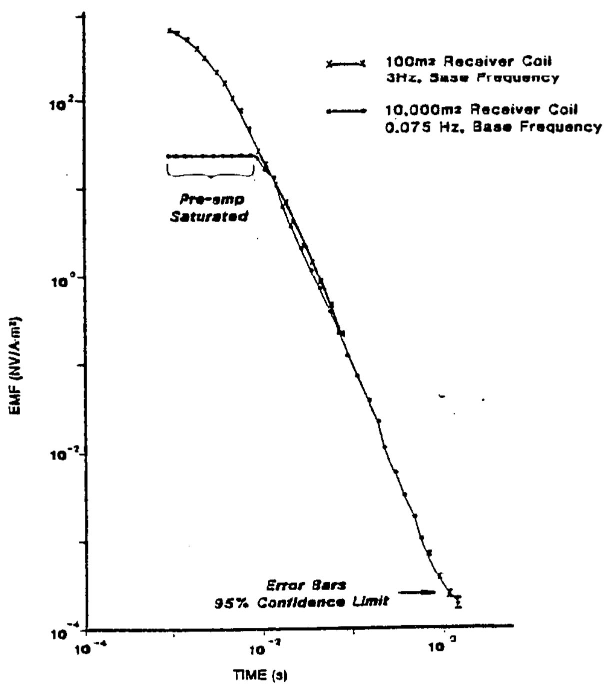


FIG. 6. Emf$_z$ measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

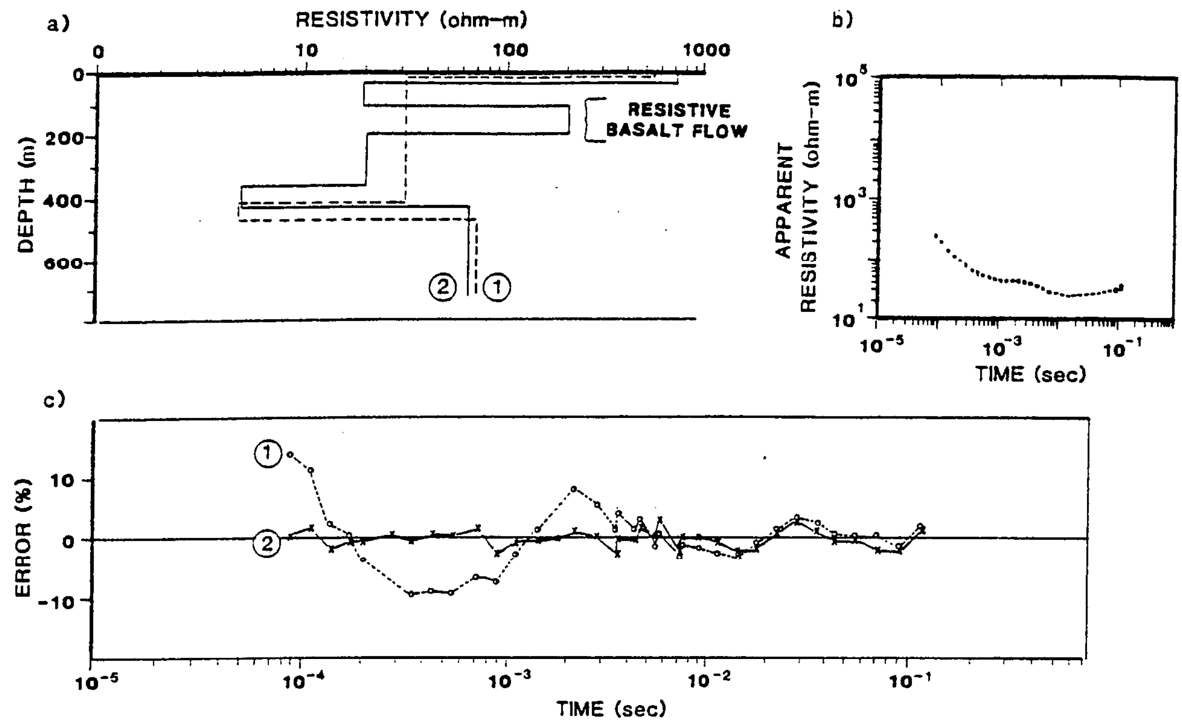


FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand soundings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

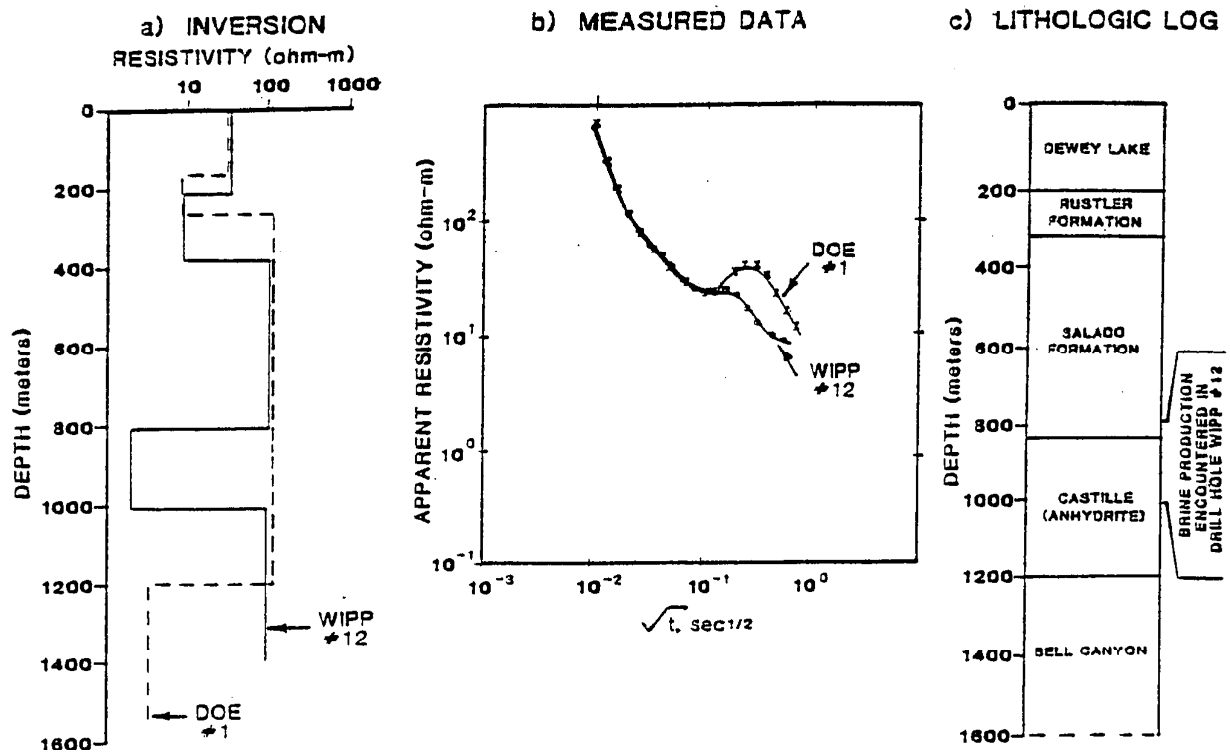


FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panels and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimensions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42.

Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a., and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth (TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addressed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

(1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

(2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

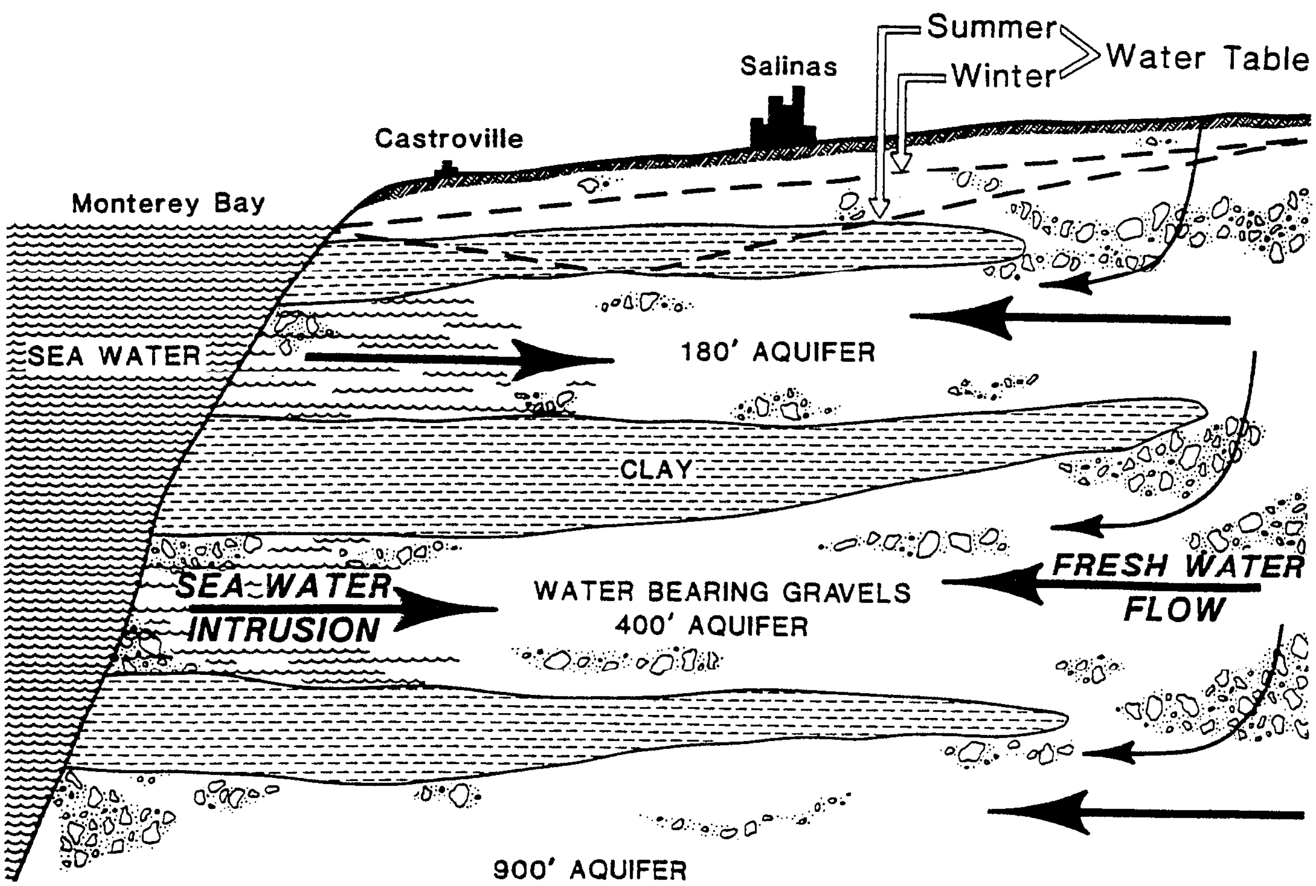


FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B′ (Figure 12) are shown on Figure 10 along with geoelectric sections derived from 1-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B′. In the 180 ft aquifer the resistivity gradually increases inland from 1.5 Ω · m (station L24/3) to 18 Ω · m (station L10/1). In the 400-ft aquifer the resistivity increased from 6.0 Ω · m to in excess of 20 Ω · m.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately 8 Ω · m corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours (8 Ω · m formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

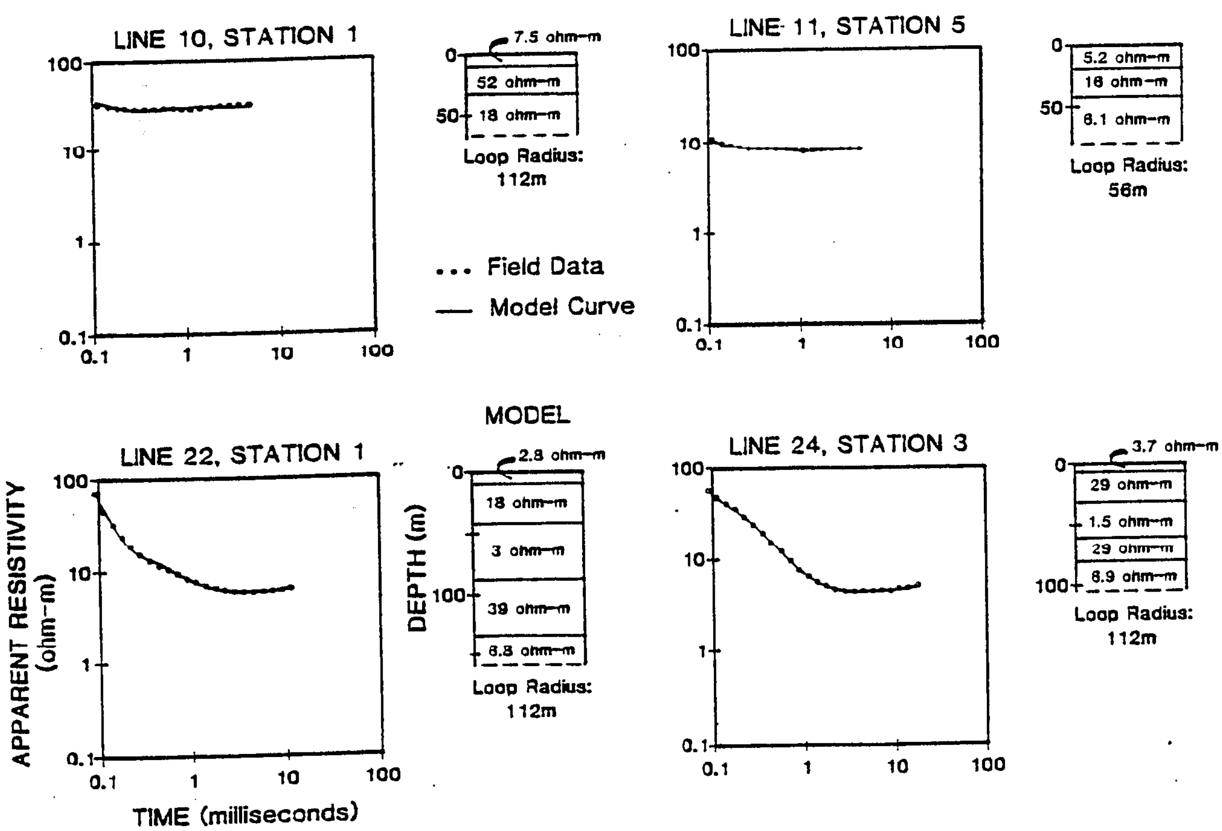


FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B′ (Figure 12).

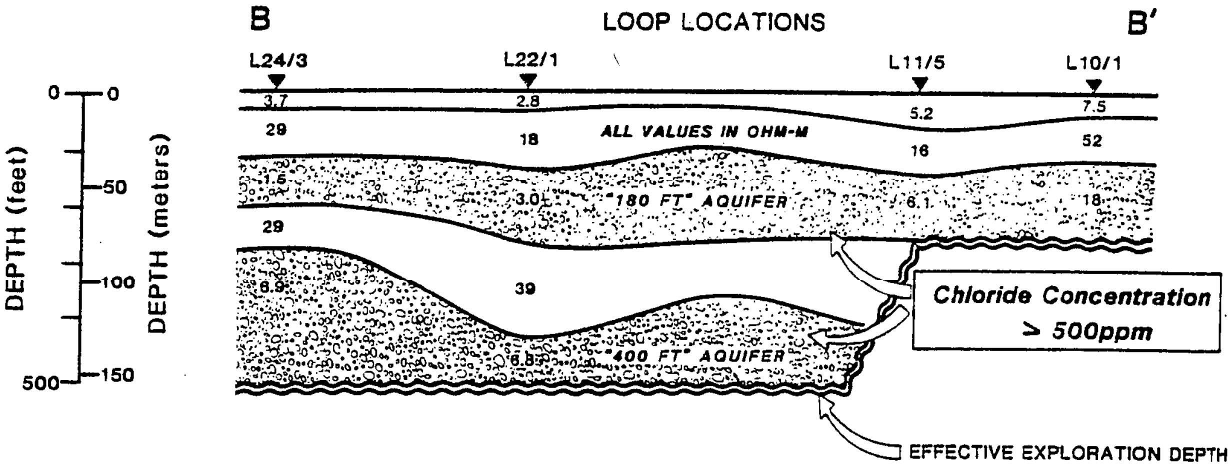


FIG. 11. Geoelectric section B-B′ derived from TDEM soundings.

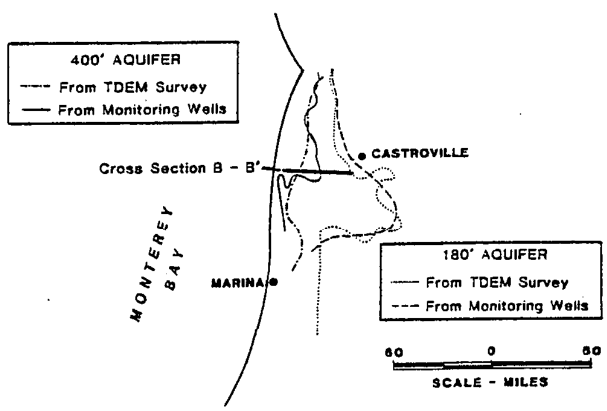


FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

(1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.
(2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for placement of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water–saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water–saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

mapping continuity of confining layers, such as clay lenses;

mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;

correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was 2.5 μs. The first time gate was centered at 6.4 μs and data were collected at base frequencies of 300 Hz and 30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops (R = 15 m), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

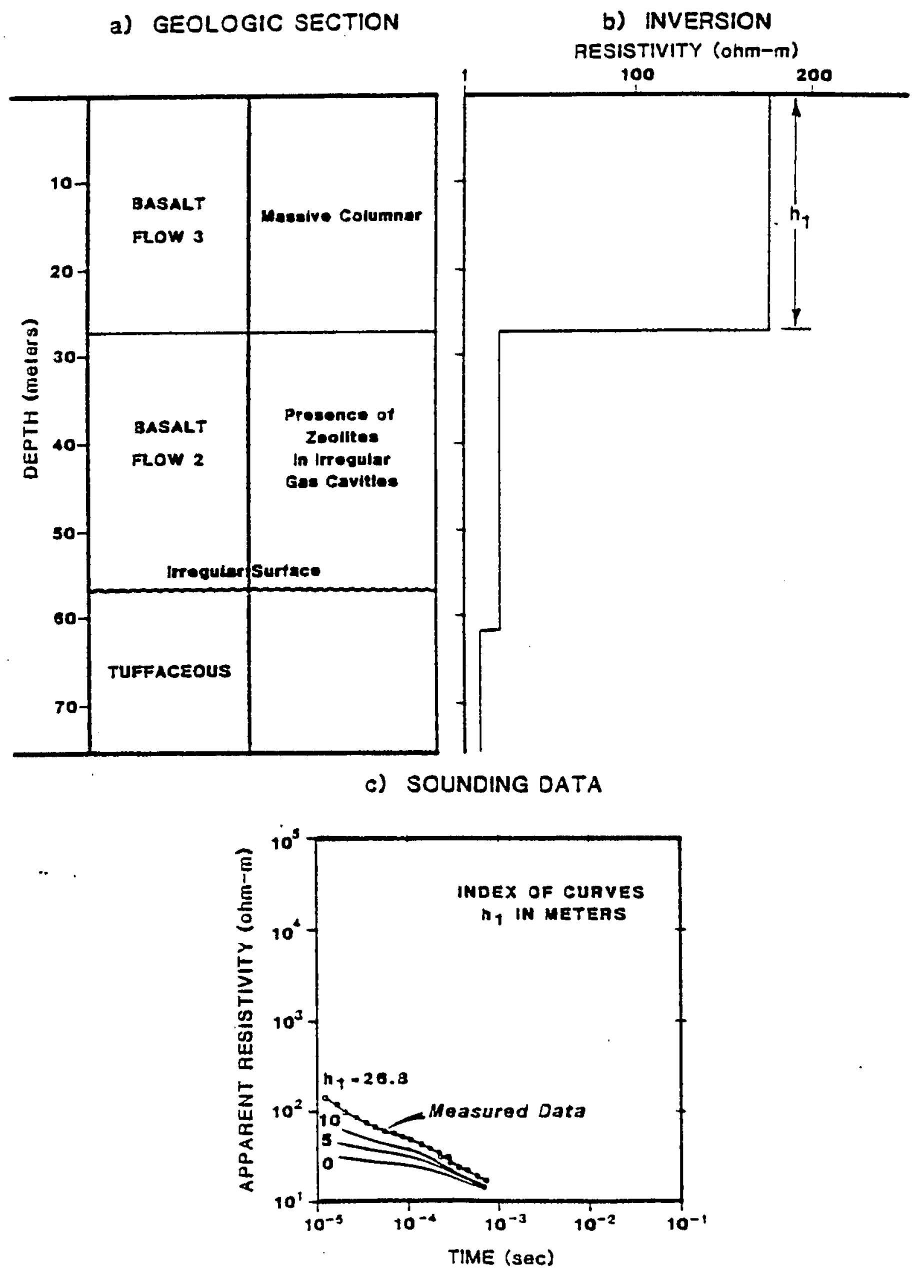


FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

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